What makes for success in science and engineering collaboratories?

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ABSTRACT
In this paper we outline the Theory of Remote Collaboration (TORC) that codifies our understanding of the major factors that lead to success in multi-institutional collaboration in science and engineering. The theory focuses on both the social interplay among the collaborators and the fit of the technologies to their work. This theory has implications for the design of technologies to support remote collaboration, to support the specific aspects that make such work successful.

INTRODUCTION
Enabled by new computing and networking capabilities, modern science and engineering increasingly involve complex, geographically distributed collaborations. These collaborations, which we call Collaboratories after Wulf (1993), connect people to expensive instruments (such as electron microscopes or earthquake engineering shake tables), to increasingly larger sets of data (such as the Protein DataBank), to each other for the basic conduct of science, or to combinations of these. For the past five years, we at Michigan have been collecting systematic data on the over 200 Collaboratories with the goal of discovering how they differ and the factors that make them successful. We have recently developed a theory, called the Theory of Remote Collaboration (TORC), that codifies our understanding of the major factors that lead to success. In this paper we outline TORC and discuss its implications for both the management of remote collaborations and areas in which new technology might enhance the chances of success.

WHAT DO WE MEAN BY SUCCESS?
One of the major complications in the development of TORC is that there are a number of ways to look at success itself. The early efforts to build Collaboratories focused on the promise of new ways of doing science with the implication that there would be new breakthroughs or more rapid progress. Of course, since such breakthroughs take time, people looked for more immediate signals of success, such as more co-authored publications, aggregating and sharing of data, wide access to expertise and instruments. But success can also be seen as changing science careers, like people being more likely to get tenure, greater diversity among scientists, and even greater quality of life (e.g.

because of reduced amount of time spent in travel). Other ways in which a Collaboratory effort might be considered successful is that it brings more students into science, it inspires the development of other Collaboratories, and that science becomes more visible and therefore more likely to be funded. In those Collaboratories that build new tools, the mere fact that the tools are used is a simple, immediate kind of success.

WHAT ARE THE FACTORS THAT LEAD TO SUCCESS?
The other complication in the development of TORC is the number and complexity of the factors that lead to success or failure on one or more of the above dimensions. We have evidence of these being important factors from two sources: the literature (from organizational behavior, the social studies of science, management, and psychology), and cases we have examined in the course of cataloging the 200 Collaboratories in our database.

The Nature of the Work
Often work requires participants to continually define and refine their understanding of what to do and how to do it because it is new, somewhat ambiguous, and highly interdependent. On many occasions, we have seen people who were not collocated attempt work that was "tightly coupled." We found either that the work was unsuccessful, or that after a period of struggle, the tightly-coupled work was reassigned to people who were collocated (Olson & Olson, 2000). Distance creates significant barriers to the frequency and richness of communication, which makes it difficult to reconcile ambiguities and keep in synch on many interdependencies (Birnholtz, 2005; Chompalov et al., 2002). Loosely coupled work, work that is easily partitionable, can be done successfully at a distance.

Common Ground
In order to make collective progress, people in a collaboration need to have mutual knowledge, beliefs, and assumptions (Clark & Brennan, 1991). For example, one particularly diverse collaboratory, the MouseBIRN of the Biomedical Informatics Research Network (BIRN), has recognized the explicit need for common vocabulary. MouseBIRN is a collaboratory that joins very different kinds of scientists all focusing on multiple levels of the mouse brain, from molecular structure to morphometry.

Recognizing that they did not all map and label the brain in the same way, they jointly built an "atlas" which, like a Rosetta Stone, shows the relationship between the terms.

If people have worked successfully together in the past, they are likely to have achieved common ground, which will improve their chance of success in subsequent collaborations. Interestingly, it also helps if the participants have a common working or management style, so that interactions and expectations are aligned. For example, those used to a strict hierarchical management style with specified deliverables and reports at various intervals will not likely function well with those used to a more egalitarian and informal style of management.

Collaboration Readiness

Understanding how people are motivated to collaborate is important, a concept we call collaboration readiness. There are a number of motivators for collaboration. The motivation could be monetary; or it could be simple recognition that people have reciprocally needed skills. For example, some collaboratories exist to share the equipment or unique skill sets of various laboratories. We have noted that when people like working together and when there is some benefit for all participants, the collaboration is more likely to succeed. On the other hand, we have seen difficulties when there are asymmetries in value to the participants, such as a mandate to include non-R1 universities in a collaboratory, or when a field is highly competitive. Additionally, when the prime motivation for collaboration is driven by funding agency requirements (i.e., in order to get funded you must collaborate), the collaboration often fails.

In a similar vein, it is important that people either trust each other or have contracts and sanctions for non-compliance (Shrum et al., 2001). The major aspects of trust are

- trust that one will not take advantage of the other's vulnerability

- "confident expectations," such as trust that others will keep their promises,

- trust that they will produce with high quality (Rousseau et al., 1998).

In one of the collaboratories that we studied, participants experienced severe mistrust when people at one location had not been informed of a policy change and were acting from a document that was, unbeknownst to them, out-dated.

Another aspect of Collaboration Readiness is that the goals of the subgroups need to be aligned (Birnholtz, 2005; Chompalov et al., 2002). For example, collaborations in which domain scientists (e.g. physics, biochemistry, etc.) and computer scientists work together to develop scientific software are often plagued by competing goals. The computer scientists see the computer system as an object of research, and want the freedom to experiment and make changes with the software. The domain scientists, on the other hand, see the system as a research tool, and need it to be hardened and reliable (Weedman, 1998).

Also, a group that feels empowered has a higher chance of succeeding than a group that does not, a concept called "collective efficacy" (Carroll et al., 2005). The empowerment is expressed in the form that the participants believe they can overcome obstacles, such as getting the work done in spite of a cut in funding.

Management, Planning and Decision Making

It is important that scientists have time and resources to commit to a collaborative project. In science, it is common to have multiple projects going at the same time. A researcher proposes work to a number of funding agencies and with some probability each gets funded. It is possible, therefore, to have too many commitments to succeed. We have found that key participants' over-commitments can be a serious problem for collaboratories.

In collaboratories that span many time zones (e.g. one international AIDS collaboratory includes researchers from the US, the UK, and South Africa), it is difficult to find times in the normal working day when real-time conversations can take place. With less overlap in the working day, participants have fewer opportunities to clarify, develop common ground, align goals, etc. All of these activities are necessary for difficult work to succeed, especially at the beginning of a project, before things have a chance of becoming less ambiguous and more routine. A key feature of science, to be sure, is that it is rarely routine.

Having a critical mass of people at each location, so that people do not feel isolated and consequently less motivated to contribute, helps a distributed collaboration to succeed. In addition, projects should designate a point person at each location who will be responsible for making sure that all participants at that location are informed and contributing. One business strategy that may work in collaboratories is including a "rotator" at each location, someone from the other location(s) to serve as the eyes and ears for the remote people (Olson & Olson, 2000).

Most federally funded proposals require a management plan. We have found on numerous occasions that having someone with good project management experience is essential. Some collaboratories find that having a scientist be project manager is important to gain respect and trust that decisions are made to further the science. Attendees at NIH's recent workshop on *Catalyzing Team Science* reported that having a "postdoc" in a managerial role was an important benefit to distributed projects, and a major recommendation of that workshop was to create career paths for those who provide infrastructure to teams (NIH, 2003). Certainly understanding the scientific domain is important, but in some cases it is wise to have a non-scientist project manager so the scientist is relieved from administrative duties (Mazur and Boyko, 1981). We have also found that collaboratories do well to have a

communication plan in place, one that clarifies expectations about when meetings will take place, who is expected to attend, how often email will be answered, etc. Interestingly, the BIRN yearly meeting is an "all-hands" meeting and everyone is expected to attend. This is a common practice in many of the collaboratories we have studied. Similarly, BIRN has committees to work on common issues (e.g. institutional review board issues), and each participating institution is expected to name someone to serve on each committee.

Occasionally, a collaboratory discovers something that is unexpected, making the original plan of work no longer appropriate. Similarly, because of issues of trust or motivation, not all parties may turn out to participate as expected. Good management allows reflection and redirection. Successful collaboratories should do this as well. Many collaboratories have oversight committees or advisory boards that can provide this function; NIH Glue Grants require them.

Even when all of the scientists are ready to proceed, collaboratories can run into institutional-related problems, especially legal issues, that cannot be resolved (Stokols et al., 2003; Stokols et al., 2005). A number of potential collaboratories have been stymied by their institutions' rigid policies about intellectual property. Some universities want to own or control what their professors discover/invent. Collaboratories that succeed have found ways to share the intellectual property and cooperate on other legal matters as well. Similarly, financial issues can be barriers. In the international AIDS research collaboratory mentioned previously, a South African university required that money be in hand before anything could be purchased, whereas the US funder would cut a check only after the purchase had been made. This impasse was finally resolved after the US and South African financial officers met in person (a trust-building move) and together worked out a compromise that fit both systems.

We have also noted that those collaboratories without good knowledge management plans often discover too late that data or records are lost. It is common for people to set up informal schemes for keeping records (e.g. minutes of meetings) only to find them inadequate when someone later tries to query the past. A key part of today's knowledge management systems is a plan to migrate data when information technology becomes obsolete. Digital preservation is an under-appreciated problem that can have costly repercussions.

Larson and his colleagues (Larson et al., 2002) found that certain aspects of collaborative decision-making were important to the success of various community projects. Decision-making needs to be free of favoritism and have fair and open criteria. It is also critical that participants have a voice, so they feel they can influence or challenge decisions. In the organizational behavior literature, this is referred to as "procedural justice" (Kurland & Egan, 1999).

Anything that negatively affects a scientist's motivation or engagement can hinder the science. Thus, while collaboratories do not need to be democracies, participants do need to feel they have some voice in the decision-making.

Technology Readiness
Virtually all collaboratories connect people via technology for both communication and core work. For technology-mediated collaborations to succeed, the participants must adopt and be able to use the tools provided. Many collaboratories use generic or commercially available tools like email, instant messaging, video or data conferencing (like Webex™ or Centra Symposium™), and basic file servers. Others use specially designed and built software, like Environmental Molecular Science Laboratory's on-line science notebook. The adoption of any technology, whether off-the-shelf or custom-designed, is driven by its fit to the work and its ease of use (Olson et al., 2000). Yet, it is difficult to create usable software for large collaborative projects. For example, early in the development of user interfaces for the Space Physics and Aeronomy Research Collaboratory (SPARC), designers spent time understanding the users' work practices in order to develop system specifications. Through user testing and other evaluation methods, the designers insured that the interface they created had the right functionality and was easy to use. Later, as individual scientists talked directly to the developers to request new features, the system became unstable as versions were released sometimes every day. Such version drift complicated the adoption and use of the system.

Similarly, scientists must feel comfortable using the technology. For example, scientists who are just learning to make efficient use of email will find it challenging to use desktop video conferencing. Interestingly, the early versions of SPARC interfaces mimicked the physical instrument displays (the same meters and dials) while the scientists got used to working online. Later, when the scientists became more comfortable with other online tools, they developed more powerful integrated displays that collected information from a variety of sources. People's beliefs in their abilities to use computers correlate highly with their adoption of technology (Compeau & Higgins, 1999).

It is also important that all essential technologies give benefit to those expected to use them. As Grudin (1988) has pointed out, if some users have to put in effort that only benefits others, the technology will not succeed. And, in the case of science, if there are motivational barriers to using the technology (e.g. no personal benefit), the technology is less likely to be adopted. In addition, if the technology is unreliable (as some research proof-of-concept prototypes can be) people will be unlikely to use it.

Interoperability is an ever-present challenge for collaborative projects. Very few applications are truly

compatible across different platforms. For example, browsers render the same web site differently and some Word documents created on a Mac cannot be read successfully on a Windows machine. Success in collaboration is greater if the participants agree on a single platform. Notably, the early SPARC software ran on a NeXT machine; part of the grant budget was spent on giving NeXT machines to all participants. Similarly, BIRN developed and configured the hardware and software centrally, and shipped it off to each participating institution, something we affectionately call "BIRN in a box."

Additionally, it helps if there is technical support at each location when technologies are complex or there are new users. Remote systems support is not adequate; computers are physical devices that need onsite technical support. To coordinate all these technical issues, it is helpful to have an overall technical coordinator. BIRN, for example, is a cluster of four collaboratories, and has in support of all of them a "coordinating center" that handles all technical issues for the cluster.

There are some special technical issues with particular types of collaboratories as well. If data sharing is the goal, standards must be agreed upon and adhered to by all participants (Hesse et al., 1993). And, as mentioned earlier with other technologies, data archiving must be planned so that as technology becomes obsolete, data integrity is maintained. If instrument sharing is part of the collaboratory, then there should be a plan to certify the users. For example, in a high-energy physics collaboratory, the operators from different countries have very different backgrounds; in Japan they are technical staff, whereas in the US, they have Ph.D.s in physics.

Summary of the thing that lead to success
The factors that lead to success include:

- The nature of the work (loosely coupled work is easier to do long distance than tightly coupled or ambiguous work);

- The amount of common ground the collaborators share (inter-disciplinary work requires a lot of work to come to common understanding of what various concepts mean and it is harder to develop trust among people from different backgrounds);

- The motivations to collaborate (when the only reason people collaborate is to secure funding, success may elude the group);

- The quality of the leadership and management; and

- The fit of the technologies to the work and the users' capabilities (what we call "technical readiness").

IMPLICATIONS OF THIS THEORY
TORC has a number of implications for the WACE community: it can guide the design of high-value technologies, it can provide a framework for conducting evaluations of existing collaborative projects, and it informs strategic planning.

Implications for design of high-value technologies
In geographically distributed projects, different information and communication technologies are often used in an effort to reproduce (or exceed (Hollan & Stornetta, 1992)) the benefits of collocated work. While collaboration technologies have yet to completely eliminate the effects of distance, many tools have made strides in helping groups to work well over distance. A common goal of many technologies, including video conferencing, email and instant messaging is to enable frequent and ongoing conversation between individuals. This approach to supporting collaboration – emulating the constant conversation that goes on in collocated environments is extremely widespread and successful.

During the course of the study of Collaboratories that led to the development of TORC, we observed a number of project teams taking a different approach to collaborative tool design. In contrast to technologies that leverage conversation to build trust and awareness, many of these projects were increasing the effectiveness of their collaborations by using technologies that specifically targeted one or more social processes related to collaboration success, using a highly specialized tool to alleviate a particular problem. In all cases, these specialized tools were used alongside general-purpose collaborative tools, but point to an alternate approach to designing collaborative tools based on the specific requirements of antecedents to collaboration success.

One example of these alternate design approaches can be found in the different ways projects have employed technology to support the establishment of common ground. A distributed engineering project held weekly technical meetings by videoconference to allow the sites involved in the project to present aspects of their work to other members of the collaboration. These meetings allowed the different sites to build a shared understanding of what was going on at other sites, but were also very important in reconciling vocabulary misunderstandings and subtle domain differences between sites that represented different scientific fields. Frequent email-list conversation supplemented these meetings. In contrast, the Mouse BIRN project (discussed above) developed a formal atlas to mediate the different languages of the sub-domains involved in the project to support database federation, but scientists have also used it to facilitate cross-domain discussions. This atlas provided a way to map different vocabularies onto each other by matching terms to spatial regions of mouse anatomy, providing a clear base for translation of different terms. A physical sciences project, on the other hand, employed data modeling to build common understandings of sub-domains, ranging from procedures to conceptual understandings of the field. These models were not based on a common grounding point, such as space. The lack of this formal grounding point and the

relative inexperience of the project team with modeling caused some serious problems for the formal completeness and validity of the data model, but the formalization of the data model was not nearly as important as the general relationships between concepts, as many data model presentations included the disclaimer "I realize this isn't proper UML, but I think it gets the point across." The value of the modeling language was as a collaboration tool rather than a modeling tool.

One commonality in each of these cases is that the projects knew that the creation of a shared understanding was a critical problem facing the collaboration. Once the problem of common ground was well understood and identified, a number of different approaches to design were possible. The distributed engineering group took a mimetic approach, using communication technologies to build and maintain common ground through constant communication, as they would do if collocated. The Mouse BIRN repurposed a technology developed to mediate human-computer communications to support human-human communication. The physical sciences project adapted a methodology intended for another purpose, benefiting from the flexibility of using it incorrectly rather than limiting its value but following all of the rules.

TORC provides guidance to technology designers by highlighting key social and organizational processes that contribute to the success of collaborations. By identifying those processes important for collaboration, TORC can help developers understand how to design technologies to specifically improve these processes in order to overcome the challenges of relying solely on general-purpose collaborative tools. In particular, TORC suggests that there are opportunities to improve collaboration support by exploring technologies that are:

- Specialized tools targeted to specific social processes in order to supplement the shortcomings of using general-purpose alone

- Abstract representations of information related to key processes, rather than mimetic approaches based on conversation

- Flexible enough to allow users to break the rules of the system in order to identify new uses or functionality.

A framework for conducting evaluations
In scientific research, evaluation is most often associated with summative evaluation that measures the outcomes of a scientific project. These outcomes often focus on the quantity and impact of publications produced, the effectiveness of clinical trials, or the development of technologies that can be adapted for public use. Less common are evaluations that focus on the processes of the science. TORC provides an opportunity for distributed projects to adopt a new orientation towards project evaluation by identifying process and outcome metrics that can be observed early and often in projects, allowing

evaluation to become a valuable tool for monitoring project progress and correcting problems along the way.

Formative evaluation is a method used widely in the field of human computer interaction to understand the requirements of systems and to evaluate existing systems or initial prototypes in order to guide further system design. Formative evaluation often employs a variety of analytical methods (e.g. checklists, modeling, heuristic evaluations) used by experts to predict potential problems or system performance. TORC can be used as a framework for these kind of analytical evaluations early in projects to provide administrators or technical coordinators with an understanding of where collaboration problems are likely to arise and how investments in process changes or technologies might preempt those problems. While TORC has not yet been used to develop or validate a modeling framework, the identification of key factors can be adapted for checklist or heuristic evaluations.

The key factors that TORC identifies also provide a framework for conducting ongoing project evaluations. By paying special attention to these processes, we believe distributed projects are much more likely to identify, understand and resolve process breakdowns as they occur, rather than leaving them unaddressed and out of control.

In providing an understanding of what factors contribute to collaboration success, TORC helps make the collaboration process measurable and understandable, enabling new kinds of evaluation for distributed scientific projects. By embracing formative and ongoing evaluations, evaluation becomes a tool for maximizing project success rather than simply measuring it after a project is complete.

A tool for strategic planning
In much the same way that TORC can be used as a framework for ongoing evaluation within a project, the theory can be used as a strategic planning tool. It can help organizations decide what kind of geographically distributed projects to participate in and how they build capacity in key areas in order to improve their ability to succeed. By providing a set of criteria for comparing different organizations, TORC provides some insight into the size and nature of the challenges that two organizations will face in trying to work with each other. By understanding the magnitude and likelihood of these challenges before committing to a joint project, organizations work to develop projects that are likely to match to their capabilities. Similarly, organizations that wish to take on more ambitious joint projects can work to build up capacity in key areas. For instance, organizations can build common ground with a particular field by hiring candidates with some background in that area or improving documentation practices to make their work more transparent to outsiders. As a strategic planning tool, TORC offers a way to help organizations systematically improve their ability to collaborate across all projects in addition to within the context of a single project.

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